

Starbursts: Lessons for the Origin and Evolution of Galaxies and the Inter-Galactic Medium

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Abstract. Starbursts are episodes of intense star-formation that occur in the central regions of galaxies, and dominate the integrated emission from the galaxy. They are a significant component of the present-day universe, being the site of $\sim 25\%$ of the high-mass star-formation. They offer unique ‘laboratories’ for testing our ideas about star-formation, the evolution of high-mass stars, and the physics of the interstellar medium. They serve as local analogs of the processes that were important in the origin and early evolution of galaxies and in the heating and chemical enrichment of the intergalactic medium. In this contribution I review starbursts from this broad cosmogonical perspective, stressing several key lessons we have learned from starbursts: 1) Violent, transient events play a significant role in the origin and evolution of galaxies. 2) Galaxies do not evolve as ‘Island Universes’: starbursts are triggered by galaxy interactions and produce outflows of hot chemically-enriched gas that ‘pollute’ the intergalactic medium. 3) Dust dramatically affects our view of high-mass star-formation in starbursts and (probably) in high-redshift galaxies. Throughout this review I emphasize the importance of space-based observations in understanding starbursts.

INTRODUCTION

What is a Starburst?

Starbursts are brief episodes of intense star-formation that occur in the central-most 10^2 to 10^3 pc-scale regions of galaxies, and dominate the overall luminosity of the galaxy. Their star-formation rates are so high that the existing gas supply can sustain the starburst for only a small fraction of the age of the universe (in agreement with detailed models of the observed properties of starbursts, which imply typical burst ages of-order 10^8 years or less). Comprehensive reviews of the starburst phenomenon may be found in the volumes edited by Leitherer et al (1991) and Franco (1997).

Starbursts are powered by high-mass stars, which I will define to have masses greater than $8 M_{\odot}$. These stars are very luminous ($L > \text{few thousand } L_{\odot}$), and so (when present in significant numbers) they dominate the energy output of a population of stars. They are also short-lived (a few million to a few-tens-of-million years) and therefore trace relatively recent star-formation. High-mass stars dominate the heating of the interstellar medium, the gas out of which new stars form. They are also the ‘thermonuclear furnaces’ that forge most of the elements heavier than He, and then disperse these heavy elements (hereafter ‘metals’) back into the interstellar medium when the dying high-mass stars explode as supernovae.

In the local universe, high-mass stars are found in both normal galaxies like our own Milky Way and in starburst galaxies. In normal galaxies they are distributed in the spiral arms throughout the ~ 30 -kpc-scale disk of the galaxy. In such galaxy disks, the existing supply of gas can sustain the current rate of star-formation for many Gigayears, consistent with a relatively slow evolution of the star-formation rate over much of the history of the universe. As already stated above, the high-mass stars formed in starburst galaxies are concentrated into a small region in the galaxy center (~ 100 times smaller than the galaxy-as-a-whole) and are the consequence of a transient event with a duration $< 10^8$ years (i.e. $< 1\%$ the present age of the universe).

High-mass stars are typically very hot ($T > 25,000$ K), and thus the luminous output of a starburst should have its peak in the vacuum-ultraviolet range ($\lambda \sim 912$ to 3000 \AA). On the other hand, starbursts are rich in interstellar gas and dust. The effective absorption cross-section of these dust grains is a strong inverse function of wavelength (cf. Calzetti 1997). The dust grains therefore absorb much of the space-ultraviolet starlight and are thereby heated to temperatures of-order 10 to 100 K. The grains then cool by emitting far-infrared radiation. Thus, samples of low-redshift starburst galaxies have come mostly from surveys that select galaxies with unusually bright ultraviolet or far-infrared emission (cf. Huchra 1977; Soifer et al 1989).

Why are Starbursts Important?

First of all, starbursts are a very significant component of our present-day universe, and as-such deserve to be understood in their own right. The most complete and well-characterized sample of starbursts is that drawn from the far-infrared IRAS survey (e.g. Soifer et al 1989). The rather strong inverse correlation between gas-depletion timescales and luminosity means that we may consider that starbursts dominate the set of galaxies lying above the ‘knee’ in the far-infrared galaxy luminosity function ($L_{IR} > \text{few} \times 10^{10} L_{\odot}$). By this reckoning, starbursts provide about 10% of the bolometric emissivity of the local Universe. Thus, starbursts are an energetically-significant phenomenon.

It is also instructive to estimate the rate of high-mass star-formation in starbursts compared to that in the disks of normal galaxies in the local universe. High-mass

stars are so hot and luminous that they are the dominant source of photons energetic enough to photoionize Hydrogen in the interstellar medium. As the ionized hydrogen recombines and the captured electron cascades to the ground-state, it emits photons. Thus, the luminosity of these Hydrogen emission-lines is a measure of the total number of high-mass stars in a galaxy. Since we know the lifetimes of these stars, this yields an average rate at which such stars must have formed in the recent past (cf. Kennicutt 1983; Leitherer & Heckman 1995). Of course the observed fluxes of the Hydrogen emission-lines must be corrected for the effects of extinction by dust. In normal galaxies (where the extinction due to dust is not severe), the optical Balmer emission-lines can be used. In dusty starbursts, infrared or mm-wave lines (which are much less affected by dust-extinction) must be used.

Applying this technique to the Kraan-Korteweg & Tammann (1979) volume-limited catalog of galaxies in the nearby universe ($D < 10$ Mpc), I find that the four most luminous circum-nuclear starbursts in the local universe (M 82, NGC 253, M 83, and NGC 4945) together comprise about 25% of the total high-mass star-formation in this volume, and the six most-actively-star-forming disks of normal galaxies contribute a comparable amount. In specific terms, the rate of high-mass star-formation in the few-hundred-parsec-scale starburst in M 82 actually exceeds the rate in the entire disk of the spiral galaxy M 101 (which has a surface area approximately four orders-of-magnitude larger than the M 82 starburst)! Thus, both in terms of total energy production and rate of high-mass star-formation, starbursts are indeed highly significant components of the present universe.

While starbursts are therefore fascinating and significant objects, they are even more important when placed in the broader context of contemporary stellar and extragalactic astrophysics. They are ideal laboratories in which to study: 1) The formation and evolution of massive stars 2) The physics of the interstellar medium under extreme conditions 3) The processes involved in the formation and early evolution of galaxies 4) The processes likely responsible for chemically-enriching and heating the intergalactic medium.

The cosmological relevance of starbursts has been dramatically underscored by one of the most spectacular discoveries in years: the existence of a population of high-redshift ($z > 2$) field galaxies (cf. Steidel et al 1996; Lowenthal et al 1997; Pettini, this volume). The number density of these galaxies implies that they almost certainly represent precursors of typical present-day galaxies in an early actively-star-forming phase. This discovery moves the study of the star-forming history of the universe into the arena of direct observations (cf. Madau et al 1996; Madau, this volume), and gives added impetus to the quest to understand local starbursts.

It is these aspects of the starburst phenomenon - the way in which nearby starburst galaxies can be used to address major issues in cosmogony - that are the subject of the rest of this contribution.

What lessons have we learned from starbursts?

Before discussing starbursts in more detail, it is useful to briefly summarize the major lessons in extragalactic astronomy and cosmology that we have learned from the study of starbursts in the local universe.

i) Violent, transient events play a significant role in the origin and evolution of galaxies.

Current interest in starbursts has been stimulated by (and has helped to create) a paradigm shift in which the importance of cataclysmic events in the evolution of galaxies has become increasingly recognized. Rather than simply evolving in a steady ‘clockwork’ fashion, galaxies may also evolve discontinuously through bursts of star-formation. This is reminiscent of the concept of ‘punctuated equilibrium’ for the evolution of biological systems.

ii) Galaxies do not evolve as ‘Island Universes’ or ‘Closed Boxes.’

There is instead two-way causal communication between galaxies and their environment: strong starbursts are triggered by the interaction or merger of two galaxies and the subsequent starbursts produce outflows of ionizing radiation and metal-enriched matter that travel into the galactic halos and possibly beyond. Further pursuing the biological analogy, this might be thought of as the ‘ecology’ of galaxy evolution.

iii) Dust in galaxies drastically affects our view of star-formation in local starbursts and (most likely) in galaxies in the early universe.

As noted earlier, the intrinsic spectral energy distribution of a young stellar population peaks in the vacuum-ultraviolet, just where the opacity of the interstellar dust grains that permeate the region of star-formation is maximal. This effect is especially relevant at high-redshifts, since the visible-light observations that provide the bulk of our information about these galaxies sample the vacuum-ultraviolet portion of their rest-frame spectrum.

THE ‘ECOLOGY’ OF STARBURSTS

The Causes of Starbursts

Starburst galaxies require the presence of substantial amounts of gas within the central-most few hundred parsecs of the galaxy. The relatively low efficiency of stars for energy production ($E \sim 10^{-3} M_{star} c^2$), coupled with the severe energetic demands (ranging from $\sim 10^{59}$ ergs for a modest starburst like M 82 up to $\sim 10^{61}$ ergs for an ‘ultraluminous’ starburst like Arp 220) mean that interstellar gas masses of at least 10^8 to $10^{10} M_{\odot}$ are needed to ‘fuel’ a starburst (even assuming 100% efficiency for the conversion of gas into stars). Indeed, mm-wave interferometric maps of the

molecular gas in powerful starbursts provide direct observational evidence for such material (cf. Sanders & Mirabel 1997).

As Larson (1987), Elmegreen (1997), and others have argued, the surface mass density of the cold interstellar matter in starburst nuclei is so high (typically of order $10^3 \text{ M}_\odot \text{ pc}^{-2}$), that the growth time for gravitational instabilities that would lead to star-formation in the starburst is extremely short (\sim a million years). Moreover, the timescales for gas depletion in a starburst via star-formation and/or supernova-driven outflows (see section 3.2 below) are also short compared to the minimum time it would take gravity to move material into the starburst from the large-scale disk of the galaxy (10^7 to 10^8 years vs. 10^8 to 10^9 years respectively). Larson therefore argues that since the gas that fuels the starburst must be assembled at least as fast as it is consumed, and since the gas has a mass comparable to the entire mass of the interstellar medium in a normal galaxy, powerful starbursts can only occur when some process allows a substantial fraction of the interstellar medium of a galaxy to flow inward by at least an order-of-magnitude in radius at velocities that are comparable to the orbital velocities in the galaxy's disk.

By way of illustration, Larson emphasizes that the collapse of a self-gravitating system implies a maximum infall rate of roughly $25 (v_{\text{infall}}/50 \text{ km s}^{-1})^3 \text{ M}_\odot$ per year. This can be compared to typical estimated star-formation rates of 10 to 100 M_\odot per year in starbursts and typical orbital velocities of roughly 150 km s^{-1} in the 'host' galaxy of the starburst (e.g. Lehnert & Heckman 1996b). To summarize, the fueling of a starburst requires a mechanism that can induce non-circular motions that are both large in amplitude and involve a substantial fraction of the interstellar medium of the galaxy.

Fortunately, these theoretical or heuristic arguments are supported by observational evidence. As samples of increasingly luminous starbursts are examined, the strength of the evidence that they are strongly interacting or merging systems also increases (cf. Sanders & Mirabel 1997). Such evidence is mostly morphological: 1) The presence of two or more nuclei within a single distorted envelope (consistent with a nearly-complete merger of two galaxies). 2) The presence of a second galaxy with the requisite proximity and relative brightness, together with the bridges and long linear 'tails' that are the hallmark of tidally-interacting galactic disks (Toomre & Toomre 1972).

The physical picture that has emerged from the theoretical interpretation of increasingly-sophisticated numerical simulations (cf. Mihos & Hernquist 1994a,b) is that during the close passage of two galaxies, tidal stresses act to strongly perturb the orbits of the stars and gas in the galaxy disk. The dissipation of kinetic energy as gas collides with gas, allows the gas to become sufficiently displaced from the stars that gravitational torques act between the stars and gas to transfer significant amounts of angular momentum from the gas to the stars. The gas can thereby fall into the center of the galaxy, where it can fuel a starburst. If the passage of the two galaxies is slow and inter-penetrating enough, dynamical friction can transfer enough kinetic energy from the stars to the dark-matter halo to allow the two galaxies to merge into a single galaxy.

Such mergers or strong interactions should take a few times the galaxy rotation period (e.g. $\sim 10^9$ years), with the intense starburst phase being significantly shorter (cf. Mihos & Hernquist 1994a,b). These timescales are loosely consistent with independent estimates of starburst lifetimes, and (in any case) are quite consistent with the transient nature of starbursts.

The Byproducts of Starbursts

Perhaps the most spectacular aftermath of a starburst is the ‘life-changing’ event associated with a galaxy merger. As first suggested by Toomre (1977), it is now clear both observationally and theoretically that the merger between two disk galaxies is at least one avenue for producing an elliptical galaxy (cf. Schweizer 1992; Barnes 1995). The presence of ‘kinematically-decoupled’ cores in elliptical galaxies (central regions in which the stars have a very different angular momentum axis from the rest of the galaxy) may be a fossil record of an merger-induced starburst in the distant past (e.g. Franx & Illingworth 1988). Likewise, the so-called ‘E+A’ galaxies, whose spectra appear to be the sum of the stars found in normal elliptical (E) galaxies plus a population dominated by A stars (stars having a lifetime of 0.1 to 1 Gigayears), may be ‘post-starbursts’ systems that are intermediate in evolutionary state between merger-driven starbursts and bona-fide elliptical galaxies (cf. Zabludof et al 1997).

Another very intriguing consequence of starbursts is the ‘super star cluster’ phenomenon. Meurer et al (1995) find that typically 20% of all the vacuum-ultraviolet light (and hence $\sim 20\%$ of the high-mass stars) in starbursts is produced by very luminous stellar clusters (dubbed ‘super star clusters’ by O’Connell et al 1994). These clusters are so luminous that it is very tempting to describe them as the possible progenitors of globular clusters (cf. Whitmore & Schweizer 1995). While the relationship between the super star clusters and classical globular clusters is a matter of on-going debate (cf. van den Bergh 1995; Meurer 1995), work on the nearest such objects demonstrates that they indeed have sizes, velocity dispersions, and masses that are similar to those of typical globular clusters (Ho & Filippenko 1996a,b).

More generally, the census of high-mass star-formation in the local universe described in section 1.2 above has an very interesting implication. Adopting the ‘Copernican Principle’ (that is, assuming that our local piece of the present-day universe is representative of the universe elsewhere and elsewhen), the fact that $\sim 25\%$ of all high-mass stars are formed in starbursts would mean one of the following:

i) Operating over the history of the universe, starbursts make about 25% of *all* the stars in galaxies (not just high-mass stars). Given the central location of starbursts in galaxies and the fact that the most powerful starbursts seem to be associated with the building of elliptical galaxies via mergers, the only

plausible fossil record of these ancient starbursts would be the central parts of disk galaxies (bulges and inner disks) and elliptical galaxies. However, bulges and ellipticals are redder and older than the average disk of a spiral galaxy, so it may be difficult to make this idea hang-together quantitatively. That is, starbursts may have indeed produced $\sim 25\%$ of the stars in galaxies on-average integrated over the history of the universe, but could not be doing-so today or the central parts of galaxies would be too blue and too bright.

ii) Starbursts (unlike normal galactic disks) make only high- mass stars and therefore leave little long-term residue. By this I mean that high-mass stars are short-lived ($< \text{few} \times 10^7$ years) compared to low-mass stars (e.g. 10^{10} years for the sun). If starbursts form only high-mass stars, then shortly after the burst is over, the starburst would fade away completely, leaving only a residue of neutron stars and black holes (the ‘Cheshire Cat’ model). Leitherer (1997) reviews the evidence that starbursts may ‘manufacture’ only high-mass stars (cf. Rieke et al 1993 vs. Satyapal et al 1997). In contrast, star-formation with a normal initial mass-function extending down to well below $1 M_{\odot}$ produces stars (and hence starlight and stellar mass) that remain behind essentially forever ($>$ the age of the universe). This is in fact how we believe the large-scale disks of normal galaxies are constructed over the course of many Gyrs.

STARBURSTS AND THE INTER-GALACTIC MEDIUM

The Inter-Galactic Medium (‘IGM’) represents the mAJority of the baryonic matter in clusters of galaxies (cf. Donahue, this volume). Comparison of the total baryonic content of the universe (cf. Turner et al 1996) to the baryons located inside the visible parts of galaxies implies that perhaps as much as 80 to 90% of the baryons in the universe might reside in the IGM. The source for the heating and re-ionization of the IGM at high-redshifts is a puzzle, since the IGM is already ionized at the time the first known QSOs appear at $z \sim 5$. Ionization due to a pre-QSO phase of galaxy formation has been suggested as possibility (cf. Madau & Shull 1996; Miralda-Escude & Rees 1997; Giroux & Shapiro 1996). As I will argue below, starbursts may play a vital role not only in heating the IGM, but also in ‘polluting’ it with the heavy elements forged by high-mass stars.

The Photoionization of the IGM by Starbursts

The high-mass stars in starbursts may be a copious source of photons that are energetic enough to ionize Hydrogen and neutral Helium in the IGM. Put most simply, for star-formation with a normal initial-mass function that extends down to $0.1 M_{\odot}$ ($8 M_{\odot}$), each baryon that is incorporated into stars yields the emission of roughly 3000 (20000) photons that are capable of ionizing Hydrogen. Thus, a

little bit of star-formation could go a long way in photoionizing the IGM (especially during very early times before the earliest known QSOs appear on the scene).

However, direct observations of local starburst galaxies below the Lyman limit at 912Å using the Hopkins Ultraviolet Telescope show that only a small fraction of the total ionizing radiation produced by these starbursts (as measured by the luminosity of the Hydrogen recombination-lines) escapes into the IGM (Leitherer et al 1995; Hurwitz et al 1997). Giallongo et al (1997) have recently set an upper limit of 20% on the average fraction of ionizing radiation due to high-mass stars escaping from all galaxies out to $z \sim 1$ based on a comparison of the total amount of star-formation between $z = 0$ and $z = 1.3$ (cf. Madau, this volume) and the upper limits on the brightness of the cosmic background ionizing-radiation field in the present universe.

Thus, the role of starbursts (and high-mass stars in general) in photoionizing the IGM is still unclear. The discovery of star-forming galaxies at $z > 3$ in principle allows the spectral region below the Lyman-break to be probed directly with the new generation of 8 and 10-meter-class telescopes, and so the relative importance of high-mass stars and QSOs in photoionizing the IGM can be determined for this early epoch.

Galactic Superwinds and the ‘Pollution’ of the IGM

Over the last few years, observations have provided convincing evidence of the existence (and even the ubiquity) of ‘superwinds’ - galactic-scale outflows of gas driven by the collective effect of multiple supernovae and stellar winds in a starburst (cf. Heckman, Lehnert, & Armus 1993; Lehnert & Heckman 1996a; Veilleux, Cecil, & Hawthorn 1996). X-ray data have proved particularly crucial since they are the only direct probe of the hot gas that contains most of the mass and energy in the flow.

Soft X-ray emission (hot gas) is a generic feature of the halos of the nearest starburst galaxies (Dahlem, Weaver, & Heckman 1997). The estimated thermal energy content of this gas represents a significant fraction of the time-integrated mechanical energy supplied by the starburst, while the soft X-ray luminosity is only a few % of the supernova heating rate. These results mean that little of the mechanical energy supplied by supernovae and stellar winds in starbursts is radiated away. Thus, in principle superwinds may efficiently transport much of the mechanical energy supplied by high-mass stars into the IGM, making such stars an important heating source for the IGM (see Donahue’s contribution to this volume).

The temperature of the hot outflowing gas in starbursts is considerably cooler (few to ten million degrees) than would be expected for pure thermalized supernova+stellar wind ejecta (10^8 K). Given these temperatures, will this gas escape the galaxy gravitational potential, or will the gas remain bound and perhaps cool and return as a galactic fountain? Following Wang (1995), the ‘escape temperature’ for hot gas in a galaxy potential with an escape velocity v_{esc} is given by $T_{esc} \sim 4$

$\times 10^6 (v_{esc}/600 \text{ km s}^{-1})^2 \text{ K}$ (where I have roughly chosen parameters appropriate to a typical spiral galaxy like our own).

The gas temperatures in superwinds are observed to be independent of the galaxy rotation speed, while T_{esc} should scale as the square of the rotation speed (*modulo* the extent of the dark matter halo). Thus, it appears that the X-ray emitting gas can easily escape from dwarf galaxies undergoing starbursts (Della-Ceca et al 1996) but possibly not from the halos of the most massive starburst galaxies (Dahlem, Weaver, & Heckman 1997; Wang 1995). As Larson & Dinerstein (1975) and many others have proposed, this selective loss of metal-enriched gas from the shallowest galaxy potential wells may be the physical mechanism that underlies the strong correlation between the metal abundance of the stellar population and the escape velocity in elliptical galaxies (e.g. Franx & Illingworth 1990). In this sense, superwinds should have a particularly devastating impact on dwarf galaxies (e.g. Dekel & Silk 1986; Marlowe et al 1995).

If indeed superwinds carry substantial amounts of metal-enriched gas out of starbursts, we should see the cumulative effect of these flows in the form of a metal-enriched IGM and/or metal-enriched gaseous halos around galaxies. By now it is clear that typical MgII absorption-line systems at $z < 1$ seen in the spectra of distant QSOs arise in the metal-enriched halos of intervening galaxies (cf. Churchill, Steidel, & Vogt 1996). These galaxies appear to be normal systems (not starbursts), so it is unlikely that ‘living, breathing’ superwinds are implicated. Nevertheless, it is plausible that the metals in these galaxy halos may trace ‘fossil’ superwinds. That is, galactic halos may be polluted primarily by the episodic eruptions associated with powerful starbursts (Heckman 1997).

Can we say anything about the gas *outside* galaxies? The existence of an IGM in clusters of galaxies whose metal content exceeds that of all the stars in all the cluster’s galaxies is one of the most remarkable phenomena in extragalactic astronomy (see Donahue, this volume). Recent ASCA X-ray spectra of this gas show super-solar abundance ratios for the α -process elements like O, Ne, and Si relative to Fe (Mushotzky et al 1996). This implicates ‘core-collapse’ supernovae (the end product of high-mass stars) and - by inference - superwinds as the source of the metals in the cluster IGM (Loewenstein & Mushotzky 1996).

If most of the metals in clusters of galaxies are floating around outside galaxies, could this be true more globally in the universe? We don’t know the answer in the present-day universe, but the situation at high-redshift is very intriguing. Burles & Tytler (1996) use the detection of OVI absorption-lines in the spectra of background QSOs to estimate that the minimum metallicity of the entire gas-phase baryonic component of the universe at $z \sim 1$ is > 0.02 h solar for $\Omega_{B,gas} = 0.01 \text{ h}^{-2}$. This is a lower limit, because it assumes all the Oxygen is the form of OVI and that the detected OVI absorption-lines are optically-thin. At $z > 2$, the presence of metals in the ‘Ly α forest’ (the ‘cloudy’ component of the early IGM) is certainly suggestive of the dispersal of chemically-enriched material by early superwinds (cf. Cowie et al 1995; Tytler et al 1995; Madau & Shull 1996). The Ly α forest material appears to have a metallicity of about 10^{-2} solar, but a high ratio of Si/C that is

suggestive of core-collapse supernovae as the source of metals (Cowie et al 1995; Giroux & Shull 1997). Given the above indications of a metal-enriched IGM at high- z , do we see any *direct* evidence for the outflow of metal-enriched gas from starburst galaxies in the early universe? We will return briefly to this in section 4.2 below.

The relatively large inferred masses of the X-ray emitting gas in local superwinds imply that we are primarily observing emission from ambient gas that has been ‘mass-loaded’ in some way into the superwind (cf. Suchkov et al 1996; Hartquist et al 1997; Della Ceca et al 1996). That is, each supernova explosion on-average must heat and eject a few hundred M_{\odot} worth of gas up to of-order 10^7 K. The large amount of mass-loading implies that the ratio of gas that is blown out of the starburst compared to the mass that is turned into stars ranges from of-order unity (if a normal complement of low- mass stars is formed in the starburst) to of-order ten (if only high-mass stars are formed). To the extent that local starbursts are analogs to forming galaxies, this suggests that galaxy formation may have been an inefficient process with only a minority of the initial complement of baryons being retained and converted into stars and the majority expelled into galactic halos or the IGM.

STARBURSTS IN THE ULTRAVIOLET

Local Starbursts as a ‘Training Set’

Observations in the vacuum-UV spectral regime ($\lambda \sim 912$ to 3000 \AA) are crucial for both understanding local starbursts, and for relating them to galaxies at high-redshift. Not only is this the energetically-dominant spectral region for the hot stars that power the starburst, this is the spectral regime where we can most clearly observe the direct spectroscopic signatures of these hot stars. Moreover, the vacuum-UV contains a wealth of spectral features including the resonance transitions of most cosmically- abundant ionic species. These give UV spectroscopy a unique capability for diagnosing the (hot) stellar population and the physical and dynamical state of gas in starbursts.

Since ground-based optical observations of galaxies at high- redshifts sample the vacuum-UV portion of their rest-frame spectrum, we can not understand how galaxies evolved without documenting the vacuum-UV properties of galaxies in the present epoch. In particular, a thorough understanding of how to exploit the diagnostic power of the rest-frame UV spectral properties of local starbursts will give astronomers powerful tools with which to study star-formation and galaxy-evolution in the early universe.

The vacuum-UV spectra of starbursts are characterized by strong absorption features, as seen in Figure 1. These absorption features can have three different origins: stellar winds, stellar photospheres, and interstellar gas. Detailed analyses of Hubble Space Telescope (HST) and Hopkins Ultraviolet Telescope (HUT) spectra of starbursts show that the resonance lines due to species with low-ionization potentials (OI, CII, SiII, FeII, AlII, etc.) are primarily interstellar in origin. In contrast, the resonance lines due to high-ionization species (NV, SiIV, CIV) can contain significant contributions from both stellar winds and interstellar gas, with the relative importance of each varying from starburst to starburst (cf. Conti et al 1996; Leitherer et al 1996; Heckman & Leitherer 1997; Gonzalez-Delgado et al 1997). The most unambiguous detection of stellar photospheric lines is provided by excited transitions, but these lines are usually rather weak (cf. Heckman & Leitherer 1997).

We (Heckman et al 1997 - hereafter H97) have just completed an analysis of the vacuum-UV spectroscopic properties of a large sample of starburst galaxies in the local universe using the data archives of the International Ultraviolet Explorer (IUE) satellite. Taken together with the results of previous studies of starbursts in the vacuum-UV, the principal lessons we have learned are as follows:

First, dust has a profound effect on the emergent UV spectrum.

As noted above, the luminous output of a starburst should have its peak in the vacuum-ultraviolet range ($\lambda \sim 912$ to 3000 \AA). On the other hand, starbursts are rich in interstellar gas and dust, and the effective absorption cross-section of these

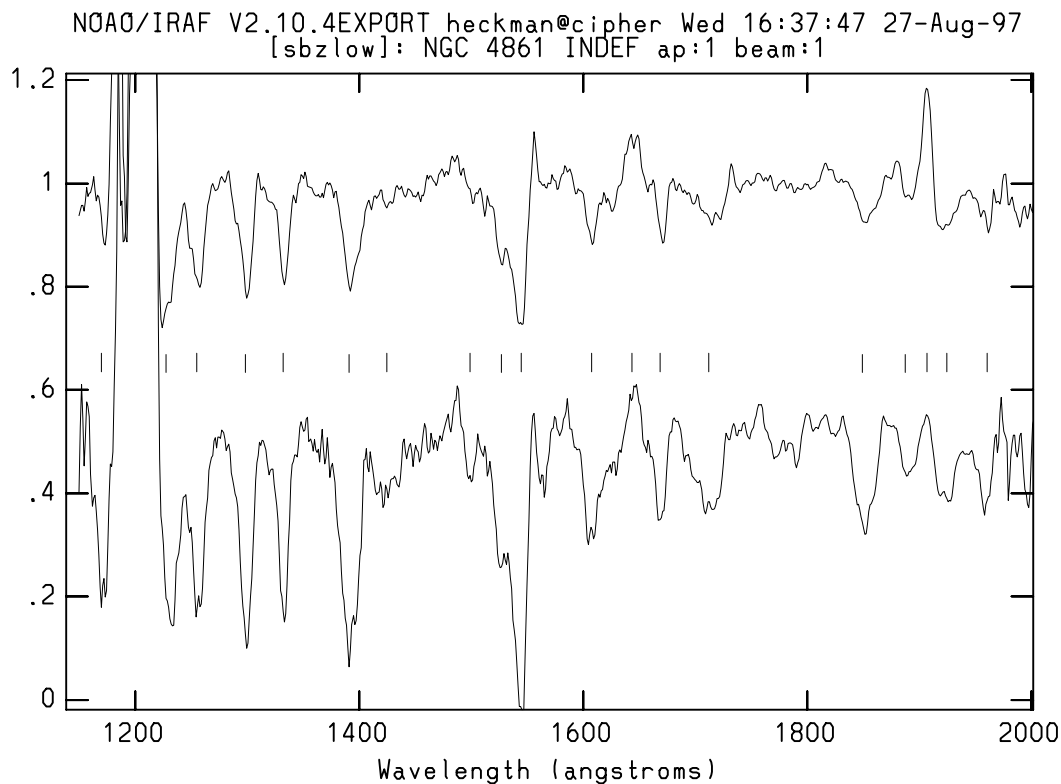


FIGURE 1. IUE spectra of local starbursts with low-metallicity (top) and high-metallicity (bottom). Each spectrum is a weighted average of the spectra of about 20 starbursts. The mean metallicities are 0.2 solar (top) and 1.3 solar (bottom). A number of features are indicated by tick marks and have the following identifications (from left-to-right): CIII λ 1175 (P), NV λ 1240 (W), SiII λ 1260 (I), OI λ 1302 plus SiII λ 1304 (I), CII λ 1335 (I), SiIV λ 1400 (W;I), SiIII λ 1417 plus CIII λ 1427 (P), SV λ 1502 (P), SiII λ 1526 (I), CIV λ 1550 (W;I), FeII λ 1608(I), HeII λ 1640 emission (W), AlII λ 1671 (I), NIV λ 1720 (W), AlIII λ 1859 (I;W), SiIII λ 1892 (P), CIII] λ 1909 (nebular emission-line), FeIII λ 1925 (P), FeIII λ 1960 (P). Here, I, P, and W denote lines that are primarily of interstellar, stellar photospheric, or stellar wind origin. The strong emission feature near 1200 Å is geocoronal Ly α .

dust grains is a strong inverse function of wavelength. This means that the effect of dust on the vacuum-UV properties of starbursts is profound.

Previous papers have established that various independent indicators of dust extinction in starbursts observed with IUE correlate strongly with one another. Calzetti et al (1996) show that the spectral slope in the vacuum-UV continuum (as parameterized by β , where $F_\lambda \propto \lambda^\beta$) correlates strongly with the nebular extinction measured in the optical using the Balmer decrement. Meurer et al (1995;1997) show that β correlates well with the ratio of far-IR to vacuum-UV flux: the greater the fraction of the UV that is absorbed by dust and re-radiated in the far-IR, the redder the vacuum-UV continuum. The interpretation of these correlations with β in terms of the effects of dust are particularly plausible because the *intrinsic* value for β in a starburst is a robust quantity. Figures 31 and 32 in Leitherer & Heckman (1995) show that β should have a value between about -2.0 and -2.6 for the range of ages and initial mass functions appropriate for starbursts (cf. Leitherer 1997).

Our detailed understanding of the above results is incomplete, since they must involve both the geometrical distribution of the dust, stars, and gas in the starburst and the vacuum-UV extinction law for the dust. However, the available data strongly suggest that (quite surprisingly) much of the dust responsible for the vacuum-UV extinction is apparently distributed around the starburst in the form of a moderately inhomogeneous foreground screen or ‘sheath’ surrounding the starburst (Gordon, Calzetti, & Witt 1997).

Interestingly, H97 find that the amount of vacuum-UV extinction in starbursts correlates strongly with the bolometric luminosity of the starburst: only starbursts with $L_{bol} < \text{few} \times 10^9 L_\odot$ have colors expected for an unreddened starburst and have vacuum-UV luminosities that rival their far-IR luminosities. Starbursts that lie at or above the ‘knee’ in the local starburst luminosity function ($L_{bol} > \text{few} \times 10^{10} L_\odot$ - cf. Soifer et al 1987) have red UV continua ($\beta \sim -1$ to $+0.4$) and are dominated by far-IR emission ($L_{IR} \sim 10$ to $100 L_{UV}$). We also find that the amount of vacuum-UV extinction in starbursts correlates well with the absolute blue magnitude and the rotation speed of the galaxy ‘hosting’ the starburst: starbursts in more massive galaxies are more dust-shrouded.

Second, the metallicity of the starburst also strongly affects the UV spectrum.

Apart from the effects of dust, a starburst’s metallicity is the single most important parameter in determining its vacuum-UV properties. In fact, metallicity and the effects of dust are well- correlated, as shown in Figure 2.

At low metallicity ($<10\%$ solar) a significant fraction of the intrinsic vacuum-UV actually escapes the starburst ($L_{IR}/L_{UV} \sim \text{unity}$), and the vacuum-UV colors are consistent with the intrinsic (unreddened) colors expected for a starburst population ($\beta \sim -2$). In contrast, at high metallicities ($>$ solar) 90% to 99% of the energy emerges in the far-IR ($L_{IR}/L_{UV} = 10$ to 100) and the vacuum-UV colors are very red ($\beta \sim 0$). Storchi-Bergmann, Calzetti, & Kinney (1994) had previously noted

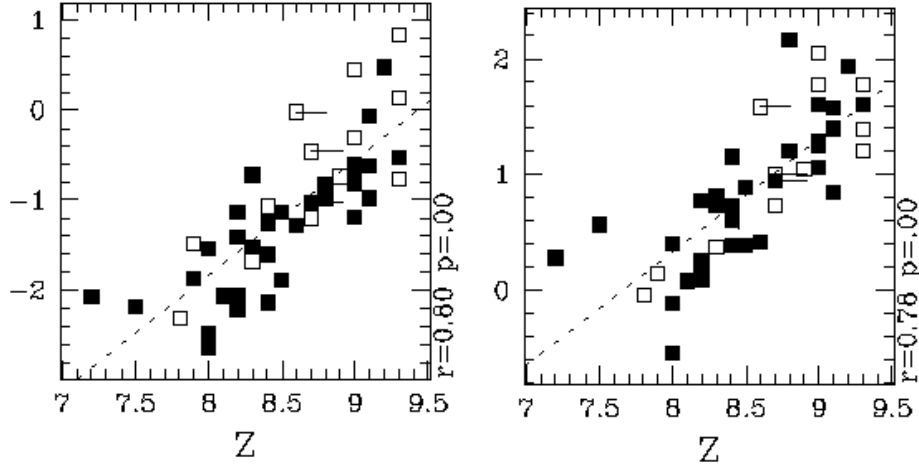


FIGURE 2. Plots of the log of the starburst metallicity (on a scale where the solar value is 8.9) *versus* two dust-indicators: the spectral slope of the vacuum-UV continuum (as parameterized by β , where $F_{\lambda} \propto \lambda^{\beta}$) and the log of the ratio of far-IR to vacuum-UV flux. Heavily-reddened and -extincted metal-rich starbursts lie to the upper right of each plot.

the correlation between metallicity and UV color.

These correlations have a straightforward interpretation: the vacuum-UV radiation escaping from starbursts suffers an increasing amount of reddening and extinction as the dust-to-gas ratio in the starburst ISM increases with metallicity. This will be true provided that neither the gas column density towards the starburst, nor the fraction of interstellar metals locked into dust grains are strong inverse functions of metallicity.

The properties of the vacuum-UV absorption-lines are also strongly dependent on metallicity. Figure 1 shows that both the high-ionization (e.g. CIV λ 1550 and SiIV λ 1400) and low-ionization (e.g. CII λ 1335, OI λ 1302, and SiIII λ 1260,1304) resonance absorption-lines are significantly stronger in starbursts with high metallicity.

The metallicity-dependence of the high-ionization lines (noted previously by Storchi-Bergmann, Calzetti, & Kinney 1994) is not surprising, given the likely strong contribution to these lines from stellar winds. Theoretically, we expect that since stellar winds are radiatively driven, the strengths of the vacuum-UV stellar wind lines will be metallicity-dependent. This is confirmed by available HST and HUT spectra of LMC and especially SMC stars (Walborn et al 1995; Puls et al 1996). If post-main-sequence stars (supergiants and Wolf-Rayet stars) contribute significantly to the integrated light, the stellar wind properties enter in a second, indirect way. That is, the integrated UV spectrum heavily depends on the evolutionary history of the OB population, which in turn is critically dependent on the stellar mass-loss rates, which in turn are a function of the metal abundance (see Maeder & Conti 1994).

Figure 1 also shows a metallicity-dependence for the strengths of the UV absorption-lines that are of stellar-photospheric rather than interstellar origin (we know they are photospheric lines because they correspond to transitions out of highly excited states). Such lines are generally rather weak in starburst spectra and/or blended with strong interstellar features. They include CIII λ 1175, SiIII λ 1417, CIII λ 1426,1428, SV λ 1502, SiIII λ 1892, and FeIII λ 1925,1960.

The weak but statistically-significant correlation between metallicity and the strength of the low-ionization resonance lines (which are primarily formed in the interstellar medium of the starburst) is also unsurprising. Analyses of HST spectra (cf. Pettini & Lipman 1995; Heckman & Leitherer 1997; Sahu & Blades 1997; Gonzalez-Delgado et al 1997) show that the strong interstellar lines are saturated (highly optically-thick). In this case, the equivalent width of the absorption-line (W) is only weakly dependent on the ionic column density (N_{ion}): $W \propto b[\ln(N_{ion}/b)]^{0.5}$, where b is the normal Doppler line-broadening parameter. Over the range that H97 sample well, the starburst metallicity increases by a factor of almost 40 (from 0.08 to 3 solar), while the equivalent widths of the strong interstellar lines only increase by an average factor of about two. This is consistent with the strong interstellar lines being quite optically-thick.

Third, the properties of the strong interstellar absorption- lines reflect the hydrodynamical consequences of the starburst, and do not straightforwardly probe the gravitational potential of the galaxy.

As noted above, analyses of HST and HUT UV spectra of starbursts imply that the interstellar absorption-lines are optically- thick. Their strength is therefore determined to first-order by the velocity dispersion in the starburst (see above). Thus, these lines offer a unique probe of the kinematics of the gas in starbursts. The enormous strengths of the starburst interstellar lines (equivalent widths of 3 to 6 Å in metal-rich starbursts) require very large velocity dispersions in the absorbing gas (few hundred km s⁻¹). Are these gas motions primarily due to gravity or to the hydrodynamical ‘stirring’ produced by supernovae and stellar winds?

Both processes probably contribute to the observed line-broadening. H97 find only a very weak (but still statistically significant) correlation between the strengths (widths) of the interstellar absorption-lines and the rotation- speed of the host galaxy. The weakness of the correlation suggests that gravity alone is not the whole story. Moreover, for any astrophysically-plausible ionic column density, the interstellar lines are typically at least twice as broad as can be explained by optically-thick gas orbiting in the galaxy potential well.

The most direct evidence for a non-gravitational origin of the gas motions comes from analyses of HST and HUT spectra, which show that the interstellar lines are often blueshifted by one-to-several-hundred km s⁻¹ with respect to the systemic velocity of the galaxy (Heckman & Leitherer 1997; Gonzalez-Delgado et al 1997; Sahu & Blades 1997; Lequeux et al 1995). This demonstrates directly that the absorb-

ing gas is flowing outward from the starburst, probably ‘feeding’ the superwinds described in section 3.2 above).

Implications at High-Redshift

The results summarized in section 4.1 have a variety of interesting implications for the interpretation of the rest-frame-UV properties of galaxies at high-redshift.

Powerful starbursts in the present universe emit almost all their light in the far-infrared, not in the ultraviolet. Thus, an ultraviolet census of the local universe would significantly underestimate the true star-formation-rate and would systematically under-represent the most powerful, most metal-rich starbursts occurring in the most massive galaxies. This may also be true at high-redshift, where the current estimates of star-formation rely almost exclusively on data pertaining to the rest-frame vacuum-UV (see Madau, this volume). For example, current samples might under-represent young/forming massive elliptical galaxies.

Using the strong correlation between the vacuum-UV color of local starbursts (β) and the ratio of far-IR to vacuum-UV light emitted by local starbursts, Meurer et al (1997) estimate that an average vacuum-UV-selected galaxy at high-redshift (e.g. Steidel et al 1996; Lowenthal et al 1997) suffers 2 to 3 magnitudes of extinction. The ‘correct’ prescription for de-extincting the high- z galaxies in order to correctly obtain the bolometric luminosity and star-formation rate is a matter of on-going debate (see the contributions by Pettini and Madau to this volume). It is worth emphasizing that the purely empirical method of Meurer et al bypasses the substantial uncertainties about the dust extinction law, and the initial mass function and age of the stellar population in the high- z galaxies (it assumes only that the high- z galaxies behave like local starbursts).

As shown recently by Burigana et al (1997), the existing limits on the far-IR/sub-mm cosmic background are consistent with the global star-formation rates inferred by Meurer et al at $z > 2$ due to dusty starbursts unless the dust in these galaxies is quite cool ($T_{dust} < 20$ K) compared to the dust in local starbursts ($T_{dust} \sim 30$ to 60 K). This seems very unlikely, since the bolometric surface-brightnesses of the high-redshift galaxies are similar to local starbursts (Meurer et al 1997), implying that the energy density of the radiation field that heats the grains is similar in the two types of objects (cf. Figure 5 and the relevant discussion in Lehnert & Heckman (1996b)).

In any case, it seems fair to conclude that the history of star-formation in the universe at early times ($z > 1$) will remain uncertain until the effects of dust extinction are better understood.

The strong correlation shown in Figure 2 between vacuum-UV color (β) and metallicity in local starbursts - if applied naively to high- z galaxies - would suggest a broad range in metallicity from substantially subsolar to solar or higher and a median value of 0.3 to 0.5 solar. This is significantly higher than the mean metallicity in the damped Ly α systems (the mAJor repository of HI gas at these

redshifts), but this may be due to selection effects: the UV-selected galaxies are the most actively star-forming regions of galaxies, while the damped Ly α systems tend to sample the outer, less-chemically-enriched parts of galaxies or perhaps proto-galactic fragments (e.g. Pettini et al 1997).

It would be interesting to use the correlations between absorption-line strengths and metallicity in local starbursts to ‘guesstimate’ the metallicity of the high- z galaxies (see Pettini, this volume). One prediction based on the local starbursts (H97) is that the high- z galaxies should show a strong correlation between the strength of the UV absorption-lines (stellar and interstellar) and β (the more metal-rich local starbursts are both redder and stronger-lined).

As noted above, Meurer et al (1997) argue that the UV-selected galaxies at high-redshift suffer substantial amounts of extinction. If their proposed extinction-corrections are applied, the high- z galaxies have very large bolometric luminosities ($\sim 10^{11}$ to 10^{13} L_{\odot} for $H_0 = 75$ km s $^{-1}$ Mpc $^{-1}$ and $q_0 = 0.1$). Interestingly, the bolometric surface-brightnesses of the extinction-corrected high- z galaxies are very similar to the values seen in local starbursts: $\sim 10^{10}$ to 10^{11} L_{\odot} kpc $^{-2}$. The high-redshift galaxies appear to be ‘scaled-up’ (larger and more luminous) versions of the local starbursts. The physics behind this ‘characteristic’ surface-brightness is unclear (cf. Meurer et al 1997; Lehnert & Heckman 1996b). However, it is intriguing that the implied average surface-mass-density of the stars within the half-light radius ($\sim 10^2$ to 10^3 M_{\odot} pc $^{-2}$) is quite similar to the values in present-day elliptical galaxies. Are we witnessing the formation of elliptical and bulges?

Finally, based on local starbursts - it seems likely that the gas kinematics that are measured in the high- z galaxies using the interstellar absorption-lines are telling us a great deal about the hydrodynamical consequences of high-mass star-formation on the interstellar medium, but rather little (at least directly) about the gravitational potential or mass of the galaxy. Even the widths of the nebular emission-lines in local starbursts are not always reliable tracers of the galaxy potential well (cf. Lehnert & Heckman 1996b). This means that it will be tricky to determine masses for the high- z galaxies without measuring real rotation-curves via spatially-resolved spectroscopy.

On the brighter side, if the kinematics of the interstellar absorption-lines can be generically shown to arise in outflowing metal-enriched gas, we can then directly study high-redshift star-forming galaxies caught in the act of ‘polluting’ the intra-cluster medium and inter-galactic medium with metals in the early universe (see section 3.2 above).

In fact, there is now rather direct observational evidence that this is the case. I will need to briefly digress to explain this evidence. As emphasized above, the interstellar absorption-lines are significantly blue-shifted with respect to the systemic velocity of the galaxy (v_{sys}) in many local starbursts. In the high-redshift galaxies there is rarely a good estimator of v_{sys} (although the weak stellar photospheric lines listed in section 4.1 above are a promising possibility in spectra with adequate signal-to-noise). It is also the case in local starbursts that the true galaxy systemic velocity lies between the velocity of the UV interstellar absorption-lines

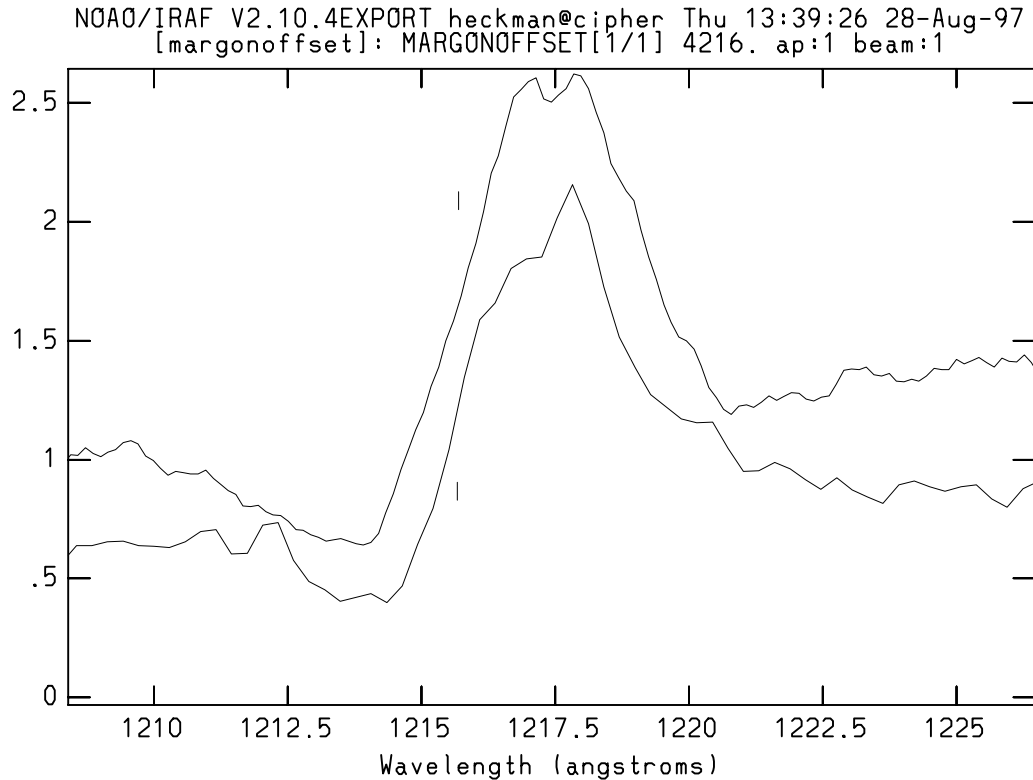


FIGURE 3. Overplot of an HST spectrum of the local starburst IRAS 0833+6517 (top - with an arbitrary offset along the y-axis) and the composite spectrum of 12 high-redshift galaxies. The rest-frame wavelength of $\text{Ly}\alpha$ at v_{sys} in IRAS 0833+6517 is indicated by the tick marks. Note the strong similarity of the two spectra with redshifted $\text{Ly}\alpha$ emission and blueshifted absorption, both due to outflowing gas. See text for details

and the $\text{Ly}\alpha$ *emission* line (Lequeux et al 1995; Gonzalez-Delgado et al 1997). This is due to outflowing gas that both produces the blue-shifted absorption-lines and absorbs-away the blue side of the $\text{Ly}\alpha$ emission-line. Thus, a purely-UV signature of outflowing gas is a blueshift of the interstellar absorption-lines with respect to the $\text{Ly}\alpha$ emission-line (even though neither is at v_{sys}).

Recently, Franx et al (1997) have seen just this effect in a spectrum of the highest-redshift object in the universe: a gravitationally-lensed galaxy at $z = 4.92$. They find that the $\text{Ly}\alpha$ emission line is redshifted by about 400 km s^{-1} relative to the $\text{SiII}\lambda 1260$ interstellar absorption-line across the entire face of the galaxy. More generally, Lowenthal et al (1997) have constructed a composite UV spectrum of 12 high- z galaxies. In Figure 3 I overplot this spectrum on an HST spectrum of the local starburst IRAS 0833+6517 (Gonzalez-Delgado et al 1997). The spectra have been aligned to force a coincidence in wavelength between the strong interstellar

absorption-lines. The similarity of the two spectra is striking: a strong redshifted Ly α emission- line and a weak blue-shifted Ly α *absorption* line. This composite spectrum strongly suggests that the outflow of metal- enriched gas at velocities of a few hundred km s⁻¹ is a generic feature of the high- z galaxies. *If* the outflowing gas escapes into the IGM, such flows could bring an IGM with $\Omega_{IGM} \sim 0.01$ h⁻² up to a mean metallicity of $> 10^{-2}$ solar by a redshift of 2.5 (cf. Madau & Shull 1996).

SUMMARY

Starbursts are defined as brief episodes ($< 10^8$ years) of intense star-formation that occur in the central-most 0.1 to 1 kpc- scale regions of galaxies and dominate the integrated emission from the galaxy. They are a significant component of the present-day universe: they provide roughly 10% of the bolometric emissivity of the local universe and are the sites of $\sim 25\%$ of the high- mass star-formation. Thus, they deserve to be understood in their own right.

They also offer unique ‘laboratories’ for testing our ideas about star formation, the evolution of high-mass stars, and the physics of the interstellar medium. They serve as local analogs of the processes that were important in the origin and early evolution of galaxies and in the heating and chemical enrichment of the intergalactic medium (IGM).

In this contribution I have reviewed starbursts from this broad cosmogonical perspective, stressing several key lessons we have learned from starbursts:

i) Violent, transient events play a significant role in the origin and evolution of galaxies. Rather than simply evolving in a steady ‘clockwork’ fashion, galaxies also evolve discontinuously through powerful bursts of star-formation, triggered by galaxy interactions.

ii) Galaxies do not evolve as ‘Island Universes’ or ‘Closed Boxes.’ Powerful starbursts are triggered by galaxy interactions and mergers that can create an elliptical galaxy out of two spirals. The starbursts produce outflows of hot metal-enriched gas (‘superwinds’) that pollute the intergalactic medium. There is now direct observational evidence for a metal-enriched IGM and for the outflows at low- and high-redshift that are responsible for this enrichment. Study of superwinds in the local universe suggest that galaxy formation may have been an inefficient process with the majority of gas being ejected.

iii) Dust dramatically affects our view of high-mass star- formation in starbursts and (probably) in high-redshift galaxies. Powerful starbursts in the present universe emit almost all their light in the far-infrared. An ultraviolet census of the local universe would significantly underestimate the true star-formation- rate and could systematically under-represent the most powerful, most

metal-rich starbursts occurring in the most massive galaxies. Applying the empirical relations followed by local starbursts to the UV-selected galaxies at high-redshift implies that the latter typically suffer 2 to 3 magnitudes of extinction, and that the star-formation rate in the universe need not be smaller at $z \sim 3$ than at $z \sim 1$. The high- z galaxies would then have estimated bolometric surface-brightnesses and sizes consistent with a population of forming elliptical galaxies.

iv) Space-based observations are crucial in understanding starbursts.

X-ray data (ROSAT, ASCA, AXAF, XMM) are vital for studying the superwind phenomenon, since they directly probe the hot gas that comprises most of the mass and energy in the flow. Ultraviolet data (IUE, HST, HUT, FUSE) offer detailed information about both the hot stars that power the starburst and the dynamics of the interstellar medium. Visible observations with the high-angular resolution of HST have revealed the importance of galaxy interactions and mergers at low and medium redshift and given us a tantalizing glimpse of the star-forming history of the early universe. Finally, the infrared (IRAS, ISO, COBE, WIRE, SIRTf, SOFIA, NGST) represents the primary channel for energy loss for the dusty, metal-rich starbursts. Such data not only document the presence of dusty starbursts in the local universe ($z \ll 1$), but also constrain their global importance at high-redshift.

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